HYPERNUCLEAR PHYSICS PROJECTS WITH PANDA AT GSI*

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Studies of $\Lambda\Lambda$-double-hypernuclei and Ω-atoms by means of γ-ray spectroscopy with Ge detectors represent a unique tool to investigate YN and YY interaction and to measure the only directly observable quadrupole moment of a hadron. These challenging experiments will be performed by the PANDA collaboration (Proton ANtiproton at DArmstadt) at the High Energy Storage Ring (HESR) of the future GSI facility. For the $\Lambda\Lambda$-double-hypernuclear γ-ray spectroscopy, a rate of several hundreds γ-ray events per day is expected.

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1. Introduction

Though fifty years have been already past since the discovery of the first hypernuclear events, studies of hypernuclei are still at the forefront of nuclear physics. In the last five years, the energy resolution for the hypernuclear spectroscopy has been drastically improved from a few MeV to a few keV by introducing γ-ray spectroscopy with Ge detectors [1]. However, we are still far away from a detailed understanding of the YN and YY interaction within $SU(3)_f$ because of lack of information on the hyperon–hyperon interaction. The GSI future facility which is planed to come into operation around 2010 will offer an excellent antiproton beam. This beam will allow to conduct high resolution spectroscopy for double-Λ hypernuclei. In the present paper, we will present the idea of γ-ray and X-ray spectroscopy for double-hypernuclei and Ω-atoms with the GSI future facility.

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2. Hypernuclear Physics with the future GSI facility

The future GSI facility will open up a new opportunity to study the nuclear system with $s=-2$ and -3. For $s=-2$ system, the study of $\Lambda\Lambda$-double-hypernuclei represents a unique approach to explore the hyperon–hyperon interaction. The search for traces of the H-dibarion in nuclear medium will be also performed. For $s=-3$ system, we will investigate Ω-atoms to measure the quadrupole moment of the Ω baryon.

2.1. $\Lambda\Lambda$-double-hypernuclei

The information on double-hypernuclei is still very limited. In 1960s, two candidates of double-hypernuclei were observed as ${}^{10}_{\Lambda\Lambda}$Be [2] and ${}^{6}_{\Lambda\Lambda}$He [3], however, the case reported in [3] is not convincing [4]. Recently, new observation on double-hypernuclei were made by the KEK-E176 and KEK-E373 experiments using an emulsion-counter hybrid detector system [5, 6]. Since the interpretation of the E176 event is not unique (${}^{10}_{\Lambda\Lambda}$Be or ${}^{13}_{\Lambda\Lambda}$B), the Λ–Λ interaction energy was extracted as -4.9 ± 0.7 MeV (repulsive Λ–Λ interaction) or $+4.8\pm0.7$ MeV (attractive Λ–Λ interaction). Here, the Λ–Λ interaction energy, $\Delta B_{\Lambda\Lambda}({}^{A}_{\Lambda\Lambda}Z)$, of double-hypernuclei with mass A and proton number Z is defined as

$$\Delta B_{\Lambda\Lambda}\left({}^{A}_{\Lambda\Lambda}Z\right) = B_{\Lambda\Lambda}\left({}^{A}_{\Lambda\Lambda}Z\right) - 2B_{\Lambda}\left({}^{A-1}_{\Lambda}Z\right) ,$$

where $B_{\Lambda\Lambda}({}^{A}_{\Lambda\Lambda}Z)$ is the binding energy of two Λs in nuclei with A and Z, defined as

$$B_{\Lambda\Lambda}\left({}^{A}_{\Lambda\Lambda}Z\right) = B_{\Lambda}\left({}^{A}_{\Lambda\Lambda}Z\right) + B_{\Lambda}\left({}^{A-1}_{\Lambda}Z\right) .$$

Table I summarizes the measured $B_{\Lambda\Lambda}({}^{A}_{\Lambda\Lambda}Z)$ and $\Delta B_{\Lambda\Lambda}({}^{A}_{\Lambda\Lambda}Z)$ for different double-hypernuclei. Apparently the $\Delta B_{\Lambda\Lambda}({}^{A}_{\Lambda\Lambda}Z)$ is varies for different nuclei. In order to interpret $\Delta B_{\Lambda\Lambda}({}^{A}_{\Lambda\Lambda}Z)$ as $\Lambda\Lambda$-binding energy, one has to consider the dynamical change of the core nucleus, $N\Lambda$ spin–spin interaction for non-zero spin of core, and the possible excited states. Particularly the last point can not be addressed by the emulsion technique. Furthermore, the usual emulsion technique is limited to very light nuclei where no neutral particles (neutrons or γ-rays) are emitted. Production experiments with double strangeness exchange (K^-, K^+) are very limited in statistics and resolution. At the high energy storage ring for antiprotons, the production of double hypernuclei will be sufficiently high to perform γ-ray spectroscopy studies with Ge detectors, thus offering a unique opportunity to study the structure both, light and heavy nuclei, with high resolution.

TABLE I

$B_{\Lambda\Lambda}(^{A}_{\Lambda\Lambda}Z)$ and $\Delta B_{\Lambda\Lambda}(^{A}_{\Lambda\Lambda}Z)$ in MeV. Note that the $^{10}_{\Lambda\Lambda}$Be and $^{13}_{\Lambda\Lambda}$B are from the same event, but different interpretation.

Nucleus	$B_{\Lambda\Lambda}(^{A}_{\Lambda\Lambda}Z)$	$\Delta B_{\Lambda\Lambda}(^{A}_{\Lambda\Lambda}Z)$	Reference
${}_{\Lambda\Lambda}{}^{6}$He	10.9 ± 0.5	4.7 ± 0.6	Prowse (1966) [3]
$^{6}_{\Lambda\Lambda}$He	$7.25 \pm 0.19^{+0.18}_{-0.11}$	$1.01 \pm 0.20^{+0.18}_{-0.11}$	KEK-E373 (2001) [5,6]
$^{10}_{\Lambda\Lambda}$Be	17.7 ± 0.4	4.3 ± 0.4	Danysz (1963) [2]
$^{10}_{\Lambda\Lambda}$Be	8.5 ± 0.7	-4.9 ± 0.7	KEK-E176 (1991) [5,6]
$^{13}_{\Lambda\Lambda}$B	27.6 ± 0.7	4.8 ± 0.7	KEK-E176 (1991) [5,6]
$^{10}_{\Lambda\Lambda}$B	12.33 ± 0.7		KEK-E373 (2001, unpub.)

2.2. H-dibaryon

The H-dibaryon is a spin and isospin singlet, positive parity state composed of six quarks ($uuddss$). It was originally predicted by Jaffe in the context of the MIT bag model more than 26 years ago [7]. Being the ground state in the $s = -2$ sector of $B = 2$ system, the H-dibaryon is stable against the strong interaction and can decay only via the weak interaction.

There have been many efforts to hunt the H-dibaryon with nuclear reaction studies, however, there have been no conclusive experimental evidence on the existence of the H-dibaryon so far. Indeed, a possible compact structure of the H-dibaryon may prevent its formation in scattering experiments because of the limited underlying time scale [8–10]. Here, the long lifetime of double hypernuclei may enable the transformation of two Λs into an H-dibaryon. Although some recent calculations suggest an unbound H-dibaryon in free space, quark-cluster-models which include hyperon mixing predict a considerably stronger binding of the H-dibaryon state in the nuclear medium [11]. For illustration, figure 1 shows the correlation functions referring to the $(3q)$–$(3q)$ relative coordinate in case of the free H-dibaryon state (left) and $^{10}_{YY}$Be ground state [11]. While for the free H-dibaryon the binding energy of $\Lambda\Lambda$ is 12.2 MeV, in $^{10}_{YY}$Be this energy is increased to 24 MeV.

As a consequence one might expect drastic changes of the decay modes, γ-ray transition probabilities and energies if the two Λ-particles inside nucleus mix with an H-dibaryon. Again, high resolution γ-ray spectroscopy and (weak) decay studies of these nuclei may help to address this issue.

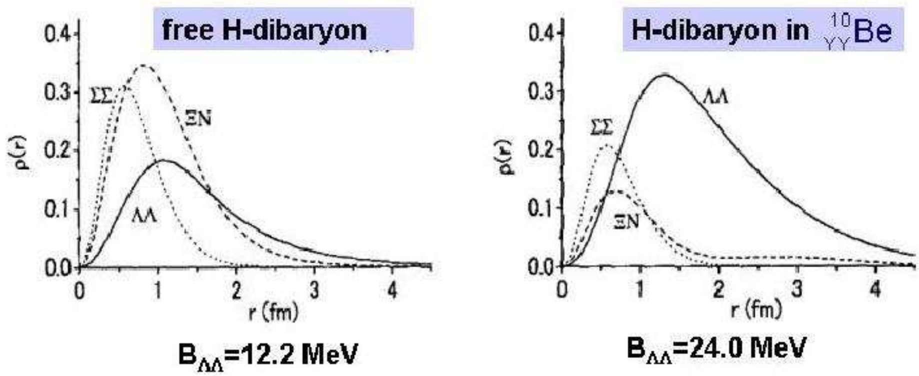

Fig. 1. Correlation functions referring to the $(3q)$–$(3q)$ relative coordinate in case of the free H-dibaryon state (left) and ${}^{10}_{YY}$Be ground state, taken from [11].

2.3. Quadrupole moment of Ω-atom

For the $s = -3$ system, we plan to extract the intrinsic quadrupole moment of the Ω-baryon (sss) by measuring Ω-atom X-rays with Ge detectors. Contributions to the intrinsic quadrupole moment of baryons are mostly one gluon exchange between quarks resulting in the occurrence of a quark tensor interaction. In general the intrinsic quadrupole moment can be expressed as

$$Q_i = \int d^3r\rho(r)(3z^2 - r^2)\,.$$

A spectroscopic quadrupole moment Q_s is proportional to

$$Q_s \propto 3J_z^2 - J(J+1)\,,$$

therefore, all $J = 1/2$ baryons have no spectroscopic quadrupole moment. Because of its spin of $J = 3/2$ and its long mean lifetime of 82 ps, the Ω-baryon is the only baryon whose quadrupole moment can be observed directly. Since it is expected that the one-gluon exchange contribution is dominating the quadrupole moment of the Ω-hyperon [12] this measurement represents a unique benchmark for our understanding of the quark–quark interaction.

We plan to measure hyper fine splitting in Ω-atoms by measuring X-rays from Ω-atom with Ge detectors. The spin–orbit interaction contributes to the energy splitting via

$$(\alpha Z)^4 l \cdot m_\Omega\,,$$

where l and m_Ω are the orbital angular momentum of Ω and its projection to the z-axis, respectively, while the electric quadrupole moment of the Ω-baryon, Q_Ω via

$$(\alpha Z)^4 Q_\Omega m_\Omega^3\,.$$

Therefore, one can extract the electric quadrupole moment of the Ω-baryon by measuring the absolute energy of the X-rays from Ω-atoms. For example, assuming $Q_\Omega = 0.028$ fm^2 and the magnetic moment of the Ω-baryon to be $-2.5\ \mu_N$, Giannini and Krivoruchenko predicted [13] X-ray energies around 520 keV for ($n = 11$, $l = 10$) to ($n = 10$, $l = 9$) atomic transitions in the ^{208}Pb Ω-atom (figure 2). The allowed transitions from ($n = 11$, $l = 10$) to ($n = 10$, $l = 9$) are also shown. The expected energies of X-rays are 518.9, 519.8, 520.8 and 521.5 keV. Although the energies of the four transitions are very close within 3 keV, spectroscopy with Ge detectors could resolve these four transitions.

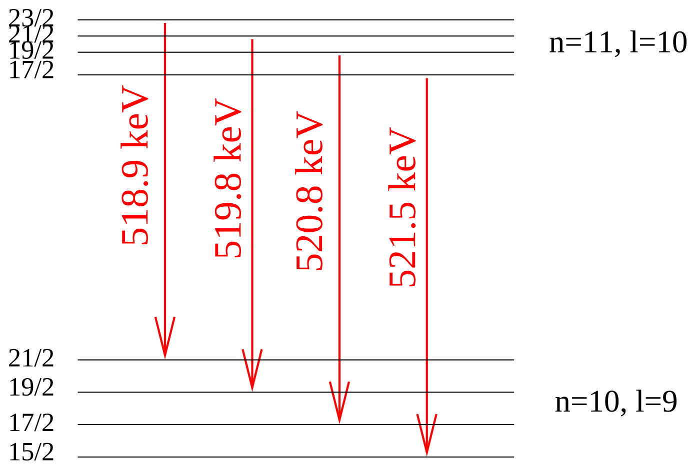

Fig. 2. The Ω-atomic levels of ($n = 11$, $l = 10$) and ($n = 10$, $l = 9$) for ^{208}Pb, predicted in [13]. Allowed transitions are shown with arrows. $Q_\Omega = 0.028$ fm^2 and μ_Ω=-2.5 μ_N are assumed.

3. GSI future project and PANDA

The GSI facility will be upgraded in the next decade, and a major component of the proposed international facility at GSI is the High Energy Storage Ring (HESR) for high intensity, phase space cooled antiprotons between 1.5 and 15 GeV/c [14]. Figure 3 shows a bird's-eye view of the planed GSI future facility including the existing facilities in the left part of the figure. At the place denoted "Panda" in the figure, HESR will be build. Figure 4 shows HESR. The momentum of stored antiproton can be varied between 1.5 and 15 GeV/c, and the expected luminosity is 2×10^{32} cm^{-2}s^{-1}. The beam is cooled by the electron cooler, therefore, a beam diameter of $10 \sim 100$ μm and a momentum dispersion of $10^{-4} \sim 3 \times 10^{-5}$ will be achieved. A general purpose detector PANDA (Proton ANtiproton at DArmstadt) will be set up at the HESR facility [15], also shown in figure 4.

Fig. 3. A bird's-eye view of the planed GSI future facility.

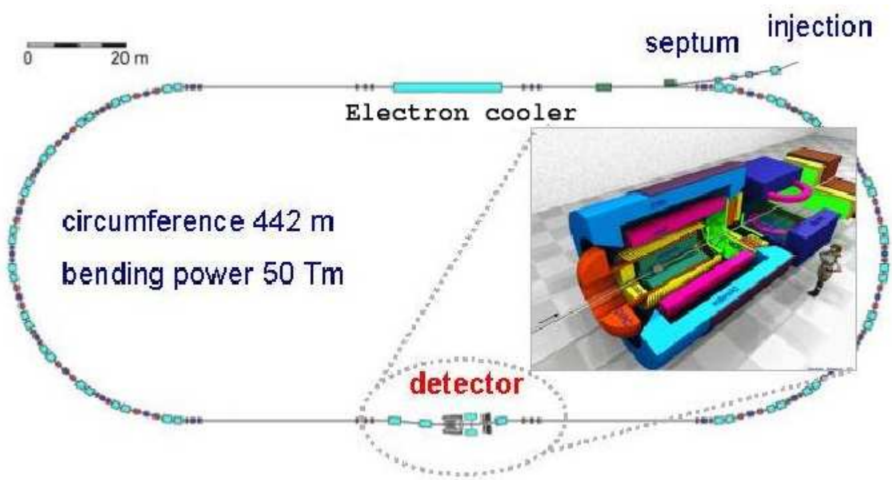

Fig. 4. HESR and the PANDA detector.

3.1. The PANDA detector and the proposed configuration for the γ-ray and X-ray spectroscopy of double-hypernuclei and Ω-atoms

The PANDA detector consists of a super-conducting solenoid magnet, straw tubes, electromagnetic calorimeters, DIRC (Detection of Internally Reflected Cherenkov light), RICH (Ring-Imaging Cherenkov detector), and a forward hadronic calorimeter (see the left panel in figure 5). The detector system is designed to be hermetic, to handle high rate events, to provide an excellent particle identification and different particle triggers, and to be modular. For the study of double-hypernuclei and Ω-atoms, we will remove the backward part of the calorimeter detector, to place a nuclear target just before the straw tubes for the production of double-hypernuclei and Ω-atoms via annihilation of antiprotons. An additional solid-state micro tracker will also be designed for this special purpose in order to obtain an excellent vertex and momentum reconstruction. At the backward angle outside of the superconducting solenoid magnet, we will mount an array of Ge detectors. It is shown in the left figure in figure 5. Because of expected high background rate due to hadronic reaction at the target, the Ge detector array has to handle very high rate including hadronic events. Presently, new fast readout electronics is being developed for this purpose. A possible option for the Ge detector array is to use the Advanced Gamma-ray Tracking Array (AGATA) which is presently under development for the study of low energy nuclear structure with intense RI beam facilities [16].

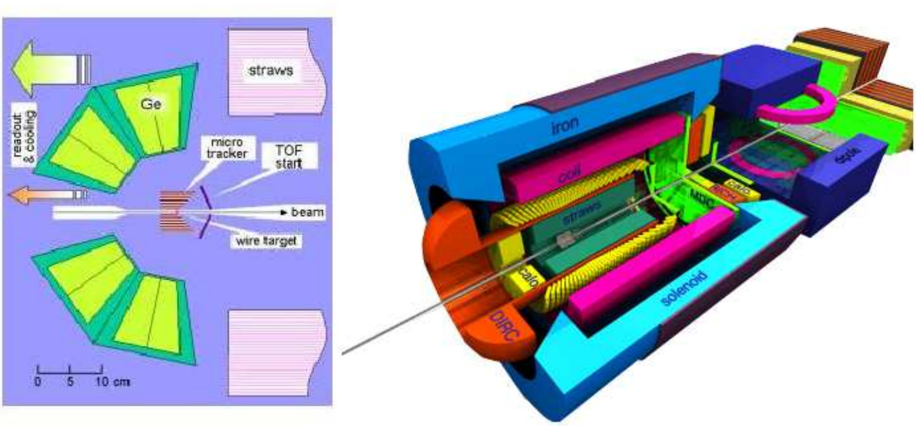

Fig. 5. The PANDA detector (left) and the configuration for the γ-ray spectroscopy of double-hypernuclei and Ω-atoms (left).

3.2. Production and the spectroscopy of ΛΛ-double-hypernuclei

For the production of $\Lambda\Lambda$-double-hypernuclei, the antiproton beam tuned at 3 GeV/c will be bombarded onto the nuclear target mounted before the straw tubes to produce pairs of $\Xi\ \bar{\Xi}$. The cross section is expected to be around 2 μb. The schematic picture describing the production of $\Lambda\Lambda$-double-hypernuclei is shown in figure 6. The produced $\bar{\Xi}$s which escape this primary target are detected directly by the PANDA detector. However, most of produced $\bar{\Xi}$ will annihilate inside the primary target nucleus. In this case the produced kaons will serve as a trigger. In the target, produced Ξs are scattered and will be captured in a secondary target forming Ξ-atoms. Bound Ξ will meet protons in the nuclear core, then the $\Xi + p \rightarrow \Lambda\Lambda$ reaction occurs. Here, the most important feature for producing $\Lambda\Lambda$-double-hypernuclei via this reaction is the fact that the Q-value of the $\Xi + p \rightarrow \Lambda\Lambda$ is only 23 MeV, thus the sticking probability of two Λs in a common nucleus is rather high. A number of produced $\Lambda\Lambda$-double-hypernuclei will be at excited states, and γ-rays depopulating the excited states will be measured by Ge detectors mounted at the backward angle.

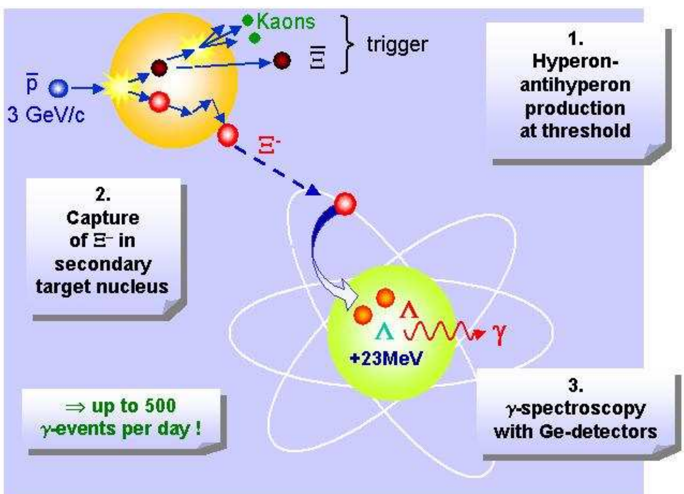

Fig. 6. The schematic picture describing how double-hypernuclei will be produced.

3.3. Production and spectroscopy of Ω-atoms

For the production of Ω-atoms, the momentum of the antiproton beam is increased to 5.5 GeV/c. The $\Omega\bar{\Omega}$ production cross section is expected maximum (around 0.1 μb) at this momentum. The produced $\bar{\Omega}$ or kaons decaying from Ω will produce triggers. The produced Ω will be captured in the atomic system in the target to form Ω-atoms, and X-rays from the Ω-atoms are measured by Ge detectors. It is clear that this experiment will benefit from studies of antiprotonic atoms at the proposed low energy antiproton facility FLAIR at GSI.

Bound Ω of course meet nucleons producing three Λs, however, because of a large Q-value of the conversion of Ω to three Λs, expected to be 203 MeV, the population of $\Lambda\Lambda\Lambda$-triple-hypernuclei will be very rare.

3.4. Expected counting rate

Assuming that the luminosity of the antiproton beam is $2{\times}10^{32}$ cm^{-2}s^{-1}, the production rate of pairs of $\Xi\bar{\Xi}$ could be 700 Hz with 2 μb cross section for the $\Xi\bar{\Xi}$ pair production at 3 GeV$/c$ antiproton beam momentum. Since we need to bound Ξ in the atomic system, a momentum range of Ξ between 100 and 500 MeV is considered. The contribution of the momentum of Ξ to this momentum range would be 0.05 . We assume a reconstruction probability of $\bar{\Xi}$ trigger to be 0.5 and the stopping and the capture probability of Ξ in the target to be 0.2. As a consequence we expect the production of Ξ-atoms is expected to be 3000 per day. If the $\Xi p \rightarrow \Lambda\Lambda$ conversion rate is 0.05, a production rate of $\Lambda\Lambda$-double-hypernuclei will be 4000 per month. Taking the efficiency of Ge detectors into account we expect a γ-ray rate for the $\bar{\Xi}$ trigger of about a few detected events per day. Using the kaon trigger, this number can be increased by up to two orders of magnitude.

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